2D Material-Based Vertical Double Heterojunction Bipolar Transistors with High Current Amplification

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The heterojunction bipolar transistor (HBT) differs from the classical homojunction bipolar junction transistor in that each emitter-base-collector layer is composed of a different semiconductor material. 2D material (2DM)-based heterojunctions have attracted attention because of their wide range of fundamental physical and electrical properties. Moreover, strain-free heterostructures formed by van der Waals interaction allows true bandgap engineering regardless of the lattice constant mismatch. These characteristics make it possible to fabricate high-performance heterojunction devices such as HBTs, which have been difficult to implement in conventional epitaxy. Herein, NPN double HBTs (DHB Ts) are constructed from vertically stacked 2DMs (n-MoS2/p-WSe2/n-MoS2) using dry transfer technique. The formation of the two P–N junctions, base-emitter, and base-collector junctions, in DHBTs, was experimentally observed. These NPN DHBTs composed of 2DMs showed excellent electrical characteristics with highly amplified current modulation. These results are expected to extend the application field of heterojunction electronic devices based on various 2DMs.

Heterostructures are widely employed in semiconducting devices to take advantage of band-structure engineering effects that lead to significantly improved carrier confinement and injection.[1] This leads to a wide variety of device performance advantages in photonic and electronic devices and over their homojunction analogs, including higher gains in transistors or brighter light outputs from the photonic devices.[2] This approach is also advantageous for mitigating the problems related to the reduction of carrier mobility as the doping concentration increases in homojunctions by separating the carriers from the dopants and also in situations where efficient bipolar doping is difficult. As a result, heterostructures have been applied to various types of semiconductor devices, such as lasers, solar cells, high electron mobility transistors, and heterojunction bipolar transistors (HBTs).[3–6] Notably, with a bipolar junction transistor, which is a three-terminal transistor fabricated by connecting two P–N homojunction diodes, there is a trade-off between the current gain and high-frequency ability because of these problems.[3,7] In sharp contrast, HBTs realized using the heterostructure can avoid these trade-offs and improve device performance.[8] HBTs, due to their high power efficiency, uniformity of threshold voltage, and low 1/f noise characteristics, have been widely used in high power amplifiers and high frequency switching devices.[3] It is challenging to realize high-quality hetero-interfaces in heterojunction devices, including HBTs owing to the various growth limitations involving mitigation of diffusion of both dopants and lattice elements. If present, these constraints contribute to performance degradation or even the complete loss of the benefits of incorporating the heterojunction.[3] For instance, III–V compound semiconductors such as GaAs/AlGaAs and GaN/AlGaN used in conventional heterojunction-based devices require high vacuum and high-cost growth equipment such as metalorganic vapor deposition (MOCVD) and molecular beam epitaxy (MBE). This growth is difficult to achieve when the difference of the lattice constants is too significant. Additionally, obstacles such as dislocation defects, strain caused by lattice mismatch, cross-contamination, and inter-diffusion are difficult to overcome. These problems cause device performance deterioration in the form of increased leakage current, a decrease of breakdown voltage, and an increase of recombination rate in HBT devices.[1–3]

2D materials (2DMs) have been studied in various fields over the past decade because of their excellent electrical, thermal, and mechanical properties.[9–13] In particular, heterostructures based on 2DMs have attracted interest because of their weak interlayer bonding, quantum effect, and tunneling, which are differentiated from conventional 3D bulk materials.[10,14] Weak van der Waals interactions of 2DMs can not only easily separate each layer, but can also layer materials regardless of lattice mismatch.[11] Additionally, because 2DMs have a sharp interface and no dangling bonds, heterostructures using 2DMs can solve problems such as atomic diffusion and dislocation propagation, which have been regarded as limitations of existing 3D bulk materials.[11,12] Selection of 2DMs provides
latitude in achieving specific electrical and optical properties because each material has a different energy bandgap, electron affinity, and carrier mobility, thereby allowing the design of desired devices to be fine-tuned without being limited by lattice constants. Roy et al. demonstrated the negative differential resistive characteristics of the Esaki diode in a hetero WSe2-MoS2 junction and analyzed its electrical and optical properties. Liu et al. fabricated P–N diodes composed of black phosphorus and MoS2 and proved that diode characteristics can be changed according to the thickness of black phosphorus. Although studies on heterostructures based on various 2DMs have been carried out, the research is still limited to fundamental structures, such as a single P–N junction diode. Even though three-terminal active devices, like HBTs and junction field-effect transistors, are more useful than two-terminal devices from the point of view of the multiple applications ranging from signal applications to the design of digital logic, those have not yet been widely studied.

This study demonstrates the highly amplified current modulation of a double HBT (DHBT), composed of vertically stacked 2DMs. MoS2, used as an n-type emitter and collector, was stacked vertically with WSe2, a p-type base, to fabricate an NPN DHBT at room temperature and atmospheric pressure. MoS2 and WSe2 are extensively used as 2D semiconductor materials. They have excellent electrical properties of electron or hole mobility and possess a tunable bandgap depending on their thickness, which enables easy bandgap engineering for the HBTs. In addition, several researchers have reported a WSe2-MoS2 type II P–N junction, which has a potential for HBTs. The NPN structure was selected because it has been reported that junction barrier for the electron is slightly lower than that for the hole carrier in WSe2-MoS2 junction. Lateral type HBTs fabricated with 2DMs have been reported by Lin et al. but vertical structure can reduce the recombination loss in the base region more efficiently than the lateral type, making very thin 2D materials even more advantageous. Double heterojunction structure was adopted because it can help avoid the difficulty of self-doping and the performance trade-off problem because of doping in contrast to a single heterojunction structure. The presence of heterojunctions in the fabricated DHBTs was confirmed through systematic analysis using transmission electron microscopy (TEM), Raman microscopy, atomic force microscopy (AFM), and electrical measurements. Our DHBT devices showed excellent electrical properties in common-emitter and common-base mode. In particular, the high current gain (β) obtained through the Gummel plot was comparable to those of commercialized III–V thin film semiconductor HBTs.

Figure 1 shows optical microscope images that depict the fabrication process of DHBTs based on 2D materials via van der Waals epitaxy (dry transfer technique). The bottom n-type MoS2 flake was first transferred onto the SiO2/Si (300 nm/525 μm) substrate (Figure 1a). Then, the p-type WSe2 and n-type MoS2 flakes were stacked vertically onto the previously transferred flake, using a micromanipulator, in the order NPN (Figure 1b,c). This procedure separated the top MoS2 from the bottom MoS2 flakes with a WSe2 layer. A Ti/Au electrode and Pd/Au electrode were defined for the MoS2 (emitter or collector) and WSe2 (base), respectively, using standard electron-beam lithography, electron-beam evaporation, and lift-off processes (Figure 1d). Figure 2a shows a schematic of the fabricated NPN DHBT, which was fabricated by stacking two MoS2 (n-type) flakes and a WSe2 (p-type) flake vertically, in the order NPN, using a dry transfer technique. Here, the top or bottom MoS2 acts as an emitter (collector) or a collector (emitter), respectively, and WSe2 in the middle layer is used as a base material. Figure 2b,c shows the AFM images and height profile of one of the fabricated devices (shown in Figure 1). The green, blue, and red dotted lines in Figure 2b indicate the bottom MoS2, WSe2, and top MoS2 flakes, respectively. The 2D flakes were ~9, ~8, ~10 nm thick, respectively. 2D flakes of similar thickness were used for other samples, and the maximum thickness did not exceed 50 nm. A cross-sectional TEM image was obtained using another fabricated DHBT sample to confirm the quality and structure of the heterostructure without strain or bubbles. This indicates that van der Waals epitaxy can prevent the lattice mismatch that occurs because of the 5.33% larger lattice constant of WSe2 compared to that of MoS2. The Raman spectra of the MoS2/WSe2/MoS2 heterostructure are shown in Figure 2d. The peaks at ~382 and ~408 cm−1 correspond to the E1g and A1g phonon modes of MoS2, respectively, and the peaks at ~248 and ~257 cm−1 correspond the E1g and A1g phonon modes of WSe2, respectively. The Raman peaks of MoS2 in the area where all three flakes overlapped were slightly broader and shifted as previous studies reported, indicating...
Figure 2. a) Schematic of an NPN DHBT grown on SiO2/Si substrate. b) AFM image of the DHBT device represented in Figure 1. The red, blue, and green dotted lines indicate the bottom MoS2, WSe2, and top MoS2 flakes, respectively. c) AFM height profile of a MoS2/WSe2/MoS2 DHBT. d) Cross-sectional TEM image of the stacked MoS2/WSe2/MoS2. e) Raman spectra of the bottom MoS2, middle WSe2, and top MoS2. The black line indicates the Raman spectra from the position at which three flakes overlap. f) Band structure of the MoS2/WSe2/MoS2 NPN DHBT.

that charge transfer occurred and a depletion layer was formed at the MoS2/WSe2 van der Waals heterojunction.[24–27] The energy band structure of the NPN DHBT is shown in Figure 2f. Several previous studies have shown that abrupt type II P–N junctions form in multilayer WSe2-MoS2 structures.[20,28–30] In bulk P–N junctions of these two materials, charge transfers occur because of the diffusion of the majority carriers. As a result, a depletion layer is formed at the WSe2 and MoS2 interfaces. A band offset with ΔEc (χWSe2 − χMoS2 = 0.45 eV) and ΔEv (EvMoS2 − EvWSe2) = 0.54 eV) obtained from Anderson’s rule indicates that the heterojunction between MoS2 and WSe2 is suitable for HBT operation.[31] The band structure shown in Figure 2f has a symmetric shape, but it is expected that an asymmetric band structure will be applied during actual operation of the device because of the orientation of top or bottom MoS2 and WSe2 and different thicknesses of the top and bottom MoS2 flakes.[32] The base thicknesses and depletion states of the NPN DHBT devices are critical for improving the performance of a device.[3,32] Although the depletion model in 2D-based P–N junctions is not fully understood, we can estimate the base thickness suitable for vertical NPN DHBT devices by calculating the width of the depletion layer using a conventional depletion model of the P–N junction. The width of the depletion layer in the p-type material can be calculated using the following equation

\[ W_d = \sqrt{\frac{2N_d e \cdot e_2 V_{bi}}{q N_a (e_1 + e_2 N_a)}} \]  

(1)

where \( q \) is the charge of an electron, \( N_d \) and \( N_a \) are the donor and acceptor carrier density, respectively, and \( e_1 \) and \( e_2 \) are the permittivity constants of MoS2 and WSe2, respectively, and \( V_{bi} \) is the built-in potential.[2] The carrier densities of the MoS2 and WSe2 were reported to be a few \( 10^{12} \) cm\(^{-2} \), and thicknesses of a few nm to several tens of nm were obtained by calculating the depletion width.[27,29,33] For example, if we assume that \( N_d, N_a, e_1, e_2, \) and \( V_{bi} \) have values of \( 3.4 \times 10^{18} \) cm\(^{-3} \) \( (n = 3.1 \times 10^{12} \) cm\(^{-2} \), \( 4.8 \times 10^{17} \) cm\(^{-3} \) \( (p = 3.8 \times 10^{11} \) cm\(^{-2} \), 12.8, 11.7, and 0.33 eV, respectively, then the estimated depletion layer width is around 29.2 nm.[27] The conventional depletion model is based on the study of intentionally doped semiconductor materials through diffusion theory; therefore, it is difficult to apply it perfectly to other materials, like 2DMs.[34] The depletion widths of van der Waals structures are known to be smaller than those predicted by conventional depletion models owing to the strong interfacial charge coupling.[27,35] Doan et al. reported that a device was not completely turned off in the WSe2 channel, which was expected to be fully depleted via the conventional depletion model, in devices composed of WSe2/MoS2 junctions.[27] Therefore, the actual depletion width of WSe2 in our NPN DHBTs might be smaller than the expected value of tens of nanometers and thus may not be completely depleted.

Electrical measurements were performed on the NPN vertical DHBTs under ambient conditions. A representative device was shown in this work, while five fabricated devices exhibited similar electrical characteristics (the optical microscope image and electrical properties of one of the other fabricated devices are included in Figure S2 in the Supporting Information). Figure 3a,b represents the typical I–V characteristics of each P–N junction of our DHBTs (the insets show the I–V characteristics on a log scale). The fabrication process and optical microscope images of the corresponding device are shown in Figure S3 in the Supporting Information. Typical rectifying behaviors of the P–N junction were observed at the base-emitter (Figure 3a) and base-collector (Figure 3b) between p-WSe2 and n-MoS2 junctions. Rectification ratios (I\(_{15\text{V}}\)/I\(_{15\text{V}}\)) were \( \approx 120 \) and \( \approx 230 \), respectively, similar to those reported by...
the previous studies.\textsuperscript{[18,28]} The ideality factor was obtained using the following equation

\[ I = I_0 \left( e^{V/nkT} - 1 \right) \]  \hspace{1cm} (2)

where \( I \) is current through the diode, \( V \) is the voltage across the diode, \( I_0 \) is dark saturation current, \( n \) is the ideality factor, \( k \) is the Boltzmann constant, and \( T \) is the absolute temperature.\textsuperscript{[36]} The ideality factors of the base-emitter and base-collector were \( \approx 10 \) and \( \approx 5 \), respectively, which are much higher than those of the ideal P–N junction.\textsuperscript{[34]} The transport of carriers in abrupt heterojunctions is usually controlled by thermionic field emission.\textsuperscript{[37]} In our devices, the ideality factor was higher because of tunneling currents, similar to what previous studies have reported.\textsuperscript{[38,39]} Problems such as polymer residue, the formation of an edge defect, and strain, which occur during the fabrication process, might have caused the high ideality factors.

The electrical characteristics of an NPN DHBT in common-emitter mode are represented in Figure 4. Here, the base-emitter (WSe\textsubscript{2}-top MoS\textsubscript{2}) was forward-biased and the base-collector (WSe\textsubscript{2}-bottom MoS\textsubscript{2}) was reverse-biased when the emitter was grounded. Figure 4a shows the input characteristics of an NPN device, which indicate the dependence of the base current on \( V_{BE} \) when the voltage bias was applied in the forward direction. A shape similar to the forward \( I–V \) characteristics of a P–N junction diode was observed. The base current decreased as \( V_{BE} \) increased and saturation began at the \( V_{CB} = +4 \) V. This indicates that the base current can be independent of the band shape because of the potential difference between the collector and emitter above \( V_{CB} = +4 \) V. Figure 4b shows the Gummel plot characteristics, where the measurement was performed...
using the conventional method that shorts the collector-to-base voltage \( (V_{CB} = 0) \).\[^{[3,7]}\] The gap of current between the collector current \( (I_C) \) and the base current \( (I_B) \) shown in the Gummel plot clearly shows that the collector current was amplified by the input of \( I_B \). Current gain \( (\beta) \) in the common-emitter mode from the Gummel plot is shown in Figure 4c and is defined as \( \beta = I_C/I_B \).\[^{[7]}\] An abnormally high \( \beta \) was observed in the low \( V_{BE} \) region (low \( I_B \) region), which might be caused by the leakage current because of the Schottky-like Ohmic contact in the base region of the device.\[^{[60–63]}\] The average value of \( \beta \) above 10 V is around 150 with a collector current density \( (J_C) \) of 1.34 A cm\(^{-2}\), which is comparable to that of conventional III–V semiconductor devices.\[^{[40,44–46]}\] The comparison between previously reported devices and our fabricated device is shown in Table 1. This shows that our results not only increase the practical possibility of 2DM-based heterojunction devices but also satisfy the performance criteria of devices grown by conventional epitaxy. Note that the fabrication process and thickness of flakes for each fabricated device are shown in Table S1 in the Supporting Information.

Furthermore, electrical characteristics in the common-base mode were measured, as shown in Figure 5a, which is similar to that of the P–N diode in the forward direction. The emitter current \( (I_E) \) increased as \( V_{CB} \) increased. This implies that the carrier movement at the emitter-base junction was affected by the band alignment change of the collector-base junction. Figure 5b shows the output characteristics in common-base mode, where the measurements were performed by injecting \( I_E (=I_{BE}) \) from 0 to 2 nA with 0.4 nA step increments. The base was grounded while \( V_{CB} \) was positive and \( V_{CB} \) was negative. It was observed that the current modulation without amplification was the same as the operation of general HBTs. \( I_C \) was almost zero when \( I_E = 0 \) nA \( (I_{CO}) \), close to zero. The current gain \( (\alpha) \) in common-base mode can be defined as \( \alpha = I_C/I_E \).\[^{[7]}\] Because \( I_{CO} \) was very small, consideration of \( I_{CO} \) was not necessary, and the value of \( \alpha \) derived from the saturation region is close to 1. These results indicate that recombination at the base region did not significantly affect the loss of carriers moving from emitter to collector. This suggests that 2DMs can provide high-quality heterojunctions with a very thin base material, which significantly contributes to the performance of the electronic devices. Our results show the potential for device fabrication using 2DMs, which has several advantages, such as bandgap engineering without consideration of lattice constant, absence of memory effects during growth, and existence of various types of 2DMs.\[^{[48]}\]

We demonstrated the fabrication of vertical NPN DHBTs using 2DMs stacking and showed efficient current amplification and modulation. Two MoS\(_2\) flakes, as an emitter and collector, and a WSe\(_2\) flake as a base, were vertically aligned in the order MoS\(_2\)/WSe\(_2\)/MoS\(_2\). The formation of the hetero P–N junction at the base-emitter and base-collector interfaces was analyzed using Raman spectra, AFM, TEM, and diode \( I–V \) characteristics. Amplified current-modulation and saturation characteristics of NPN DHBTs in common-emitter and common-base mode were observed. The maximum current gain \( (\beta) \) in common-emitter mode from the Gummel plot of the fabricated sample was \( \approx 150 \), which is comparable to that

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<td>GaN/InGaN</td>
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<td>GaN/InGaN</td>
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<td>MoS(_2)/WSe(_2)</td>
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Table 1. Comparison of device performance and properties between this work and other previously reported HBT devices.

Figure 5. a) Input characteristics of NPN vertical DHBT according to \( V_{CB} \). b) Output characteristics of NPN vertical DHBT according to \( I_E \).
of conventional HBTs based on III–V semiconductors grown under a high vacuum condition. Excellent current switching in common-base mode was also obtained. This approach is appropriate for producing rectifiers and amplifiers that meet the performance criteria established for devices produced by conventional epitaxy and processing. We believe that our study allows the fabrication of structures having new functionalities and high-performance, which was not previously possible because of lattice-mismatch, and the requirements of high-vacuum equipment.

**Experimental Section**

**Device Fabrication:** The n-type (MoS$_2$) or p-type (WSe$_2$) flakes that make up the HBTs were mechanically exfoliated from each bulk crystal (MoS$_2$: graphene supermarket, WSe$_2$: HQ graphene) using an adhesive tape and then were transferred to transparent gel film. Then, two n-type MoS$_2$ flakes and one p-type WSe$_2$ flake were stacked and placed on an adhesive tape and then were transferred to transparent gel film. A Ti/Au electrode (50/100 nm) was obtained using a micro-Raman instrument with a 532 nm diode laser, and Pd/Au electrode (50/100 nm) were defined for MoS$_2$ and WSe$_2$, respectively, using standard electron-beam lithography, electron-beam evaporation, and lift-off processes. Oxygen plasma treatment was investigated with a scanning transmission electron microscope (STEM; JEM-2100F, JEOL); the specimen was prepared using the focused ion beam (FIB) technique (Quanta 2003D, FEI) after a carbon coating was applied to protect the sample. The electrical properties of the HBTs were measured under ambient air using a semiconductor parameter analyzer (4155C, Agilent) connected to a probe station.

**Device Measurements:** The thickness of each flake was measured using an AFM (Bruker Corp.) in tapping mode. Raman spectra were obtained using a micro-Raman instrument with a 532 nm diode laser in the order NPN. A Ti/Au electrode (50/100 nm) and Pd/Au electrode (50/100 nm) were defined for MoS$_2$ and WSe$_2$, respectively, using standard electron-beam lithography, electron-beam evaporation, and lift-off processes. Oxygen plasma treatment (50 W, 25 sccm for 10–30 s) was used in a small area around the WSe$_2$/electrodes to obtain a better Ohmic contact.[23] Two electrodes were defined on each NPN flake to confirm the successful injection of the charge carriers.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

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